Paleocene non-avian dinosaurs

Spencer G. Lucas[1]

[1] New Mexico Museum of Natural History, 1801 Mountain Road N.W., Albuquerque, New Mexico, USA.

SL, 0000-0002-4594-3024.

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Corresponding author e-mail: spencer.lucas@state.nm.us

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ABSTRACT

Reports of Paleocene non-avian dinosaur fossils (hereafter simply Paleocene dinosaurs) were first published in the 1800s and, though not numerous, are now nearly global in distribution, having been claimed from all the continents except Australia and Antarctica. These reports fail to demonstrate the presence of Paleocene dinosaurs because of one or more of the following problems: (1) misidentifications of supposed Paleocene dinosaur fossils that are not dinosaurian; most of these misidentifications are of crocodilian fossils; (2) failure to establish a Paleocene age for the dinosaur fossils because of incorrect age data or stratigraphic position; and/or (3) failure to establish a clear association of dinosaur fossils that are not reworked with *bona fide* Paleocene fossils. It is not possible to determine with certainty whether a fossil tooth/bone is reworked because abrasion and other damage to the fossil is not a definite criterion for reworking. Thus, the supposed Paleocene dinosaur fossils from Montana, USA and the Chatham Islands in the southern Pacific are arguably reworked but not definitely reworked in the eyes of some palaeontologists. Still, there is no definitive evidence that these are not reworked dinosaur fossils, so there are no demonstrated Paleocene dinosaur fossils. Nevertheless, there is no reason theoretically why there should not be Paleocene dinosaur fossils, so the search for them will continue.

KEYWORDS: Cretaceous, Paleocene, dinosaur, reworked, biostratigraphy.

INTRODUCTION

The phrase “Paleocene dinosaur” is an oxymoron. This is because almost all palaeontologists see the final extinction of dinosaurs as a terminal Cretaceous event; no dinosaurs survived to live during the Paleocene. When Richard Owen (1841, p. 103) coined the term dinosaur, he recognised “a distinct tribe or sub-order of Saurian Reptiles” that consisted of the genera *Hylaeosaurus*, *Iguanodon* and *Megalosaurus*. Owen (1861) later showed the temporal range of dinosaurs, divided into herbivores and carnivores, to encompass Jurassic and part of Cretaceous time (Lucas, 1991, Fig. 1).

Nevertheless, for about 150 years, almost since the first studies on dinosaurs, diverse claims of Paleocene dinosaurs have been published (Fig. 1). Some of these claims were based on fossils misidentified as dinosaurs, and others on incorrect Paleocene (or younger) ages assigned to strata with real dinosaur specimens. However, other claims are based on *bona fide* dinosaur fossils stated to be directly associated with (or stratigraphically above) unquestionable Paleocene fossils, or other age data indicating a Paleocene age. These claims challenge the conclusion that no dinosaur occurred during the Paleocene, and almost all such claims have met with serious efforts at refutation.

The general subject of Paleocene dinosaurs has been reviewed by a few authors (Charig, 1989; Archibald, 1996; Molnar & Vasconcellos, 2016), but these reviews have not been comprehensive or (in my view) sufficiently critical of the claims. Indeed, in what is the most

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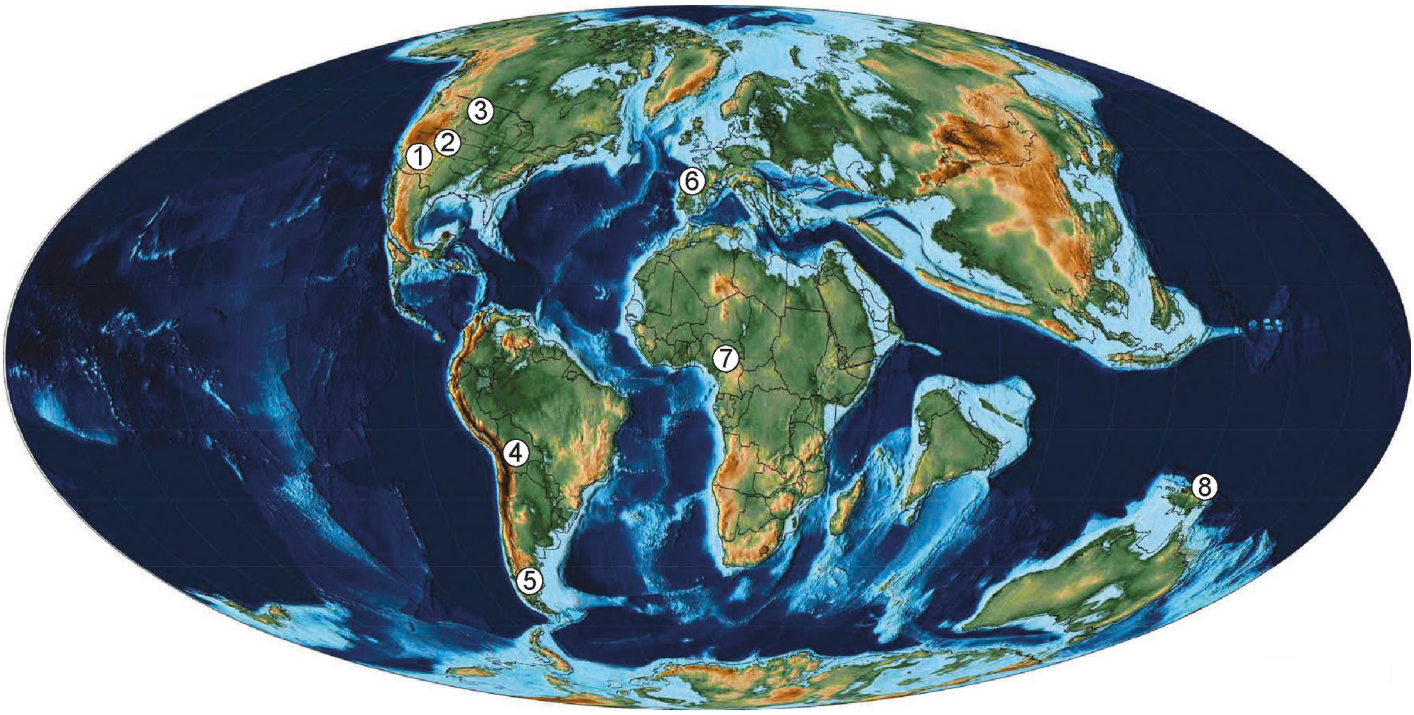

Fig. 1 - Palaeogeographic map of the world at the Cretaceous/Paleogene boundary (from CR Scotese, PALEOMAP Project) showing the locations of claims of Paleocene dinosaur fossils: 1 = San Juan Basin, New Mexico, USA; 2 = Denver Basin, Colorado, USA; 3 = eastern Montana, USA; 4 = Bolivia; 5 = Patagonia, Argentina; 6 = Asturias, Spain; 7 = Nigeria; 8 = Chatham Islands, South Pacific.

extensive review of the subject before this paper, Charig (1989) accepted the reports of Paleocene dinosaurs from Montana and New Mexico reviewed below. Charig (1989) also mentioned other possible reports of Paleocene dinosaurs from locations such as India, but he was (and I am) unaware of scientific publications on these claims.

Here, I approach the issue of Paleocene dinosaurs simply as a biostratigraphic problem. Do biostratigraphic or other geologic-age data demonstrate the presence of dinosaur fossils in Paleocene strata? Examination of this question identifies the criteria that need to be met to assign a Paleocene age to a dinosaur fossil. My conclusion is that *bona fide* Paleocene dinosaur fossils have not been documented conclusively, but I am certain that the quest for a Paleocene dinosaur will continue.

CHRONOSTRATIGRAPHY AND BIOCHRONOLOGY

Here, I make clear a few chronostratigraphic and biochronologic conventions used in this article. The Cretaceous/Palaeogene (K/Pg) boundary (called Cretaceous-Tertiary or K/T boundary in much of the literature) is the base of the Danian Stage, which is the base of the Paleocene Series. The GSSP (global stratotype section and point) that defines the base of the Paleocene is located in Tunisia with its primary signal the iridium anomaly that reflects the Chicxulub impact, and this anomaly has a numerical age of 66 Ma (Speijer et al., 2020). The iridium-rich clay layer, however, is known from only one stratigraphic section with supposed Paleocene dinosaurs, in eastern Montana (Moore et al., 2014). The correlation of dinosaur-bearing latest Cretaceous strata to the boundary level is thus accomplished primarily by biostratigraphy and magnetostratigraphy, and there has been some debate about the precision of that correlation relevant to claims of Paleocene dinosaurs.

The Paleocene Epoch is a chronostratigraphic unit that was originally proposed based on fossil plants, but that became part of the global chronostratigraphy in the 1930s because of its distinctive fossil mammals (Matthew, 1920, 1937). Thus, the oldest epoch of the Cenozoic prior to the 1930s was the Eocene, and it encompassed both the Paleocene and the Eocene of current usage. In the text below, claims of Paleocene dinosaurs made before the 1930s thus were originally stated as claims of Eocene dinosaurs.

Fossil-mammal assemblages have been used to define biochronological units termed land-mammal "ages", particularly for Cenozoic time. These are intervals of time recognised by distinctive mammalian taxa. The North American Puercan and Torrejonian LMAs, South American Casamayoran LMA and the Asian Shanghuan LMA are discussed below.

REWORKING

Before reviewing claims of Paleocene dinosaur fossils, the criteria used to identify reworking of vertebrate fossil teeth and bones merit some review, as the question of reworking is integral to the discussion of supposed Paleocene dinosaur fossils. As is well known, a reworked fossil has been moved from its original stratigraphic location to now be located in a stratum *younger* than the original one. Reworking is usually identified by damage to the fossil inferred to have occurred during erosion, exhumation,

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transport and reburial. The opposite of reworking is leakage when a fossil has moved from its original stratigraphic location to now be located in a stratum *older* than the original stratum. Microfossils are more susceptible to leakage than larger fossils.

The main criteria that have been used to identify reworked fossil teeth/bones are: (1) abrasion/damage, as just mentioned; (2) presence of isolated elements, not articulated material, which would be much more difficult to impossible to rework; and (3) the reworked fossils are out of their normal temporal/stratigraphic range. The energy of deposition/depositional environment of the fossil-bearing strata can be considered a fourth criterion to identify reworking. Depositional environments that easily promote reworking include fluvial channel deposits that scour and fill underlying strata. Bones in floodplain mudrock are likely little transported and thus not as likely to be reworked as bones in fluvial channel deposits. Marine shorelines are also places where reworking can often occur as the energy of the marine depositional system exhumes, transports and redeposits bones/teeth in high-energy shoreline settings.

A fifth criterion is the nature of fossils associated with those that may have been reworked. Thus, if marine fossils are associated with supposed Paleocene dinosaur fossils (dinosaurs did not live in marine environments) this means the dinosaur fossils were certainly transported and may have been reworked. We also do well to remember that microfossils are easily reworked or subject to leakage, especially the palynomorphs often associated with supposed Paleocene dinosaur fossils.

More than one study indicates that reworking need not produce obviously abraded/damaged teeth or bones (Argast et al., 1987; Eaton et al., 1989). Thus, Eaton et al. (1989) reviewed records of clearly reworked Cretaceous shark teeth in Paleocene and Eocene strata in Wyoming, Utah and New Mexico, to conclude that "neither the nature of preservation nor the degree of abrasion could be used to distinguish reworked from contemporaneous material" (p. 281) and noted (referring also to Argast et al., 1987) that "abrasion of specimens may tell little about reworking" (p. 285).

Argast et al. (1987) put actual fossil teeth of tyrannosaurids and crocodilians in a tumbler and ran it with quartz sand grit for 577 hours, which they estimated to represent about 360-480 km of transport. They found little to no abrasion of the teeth to conclude that "it is impossible to infer limited transport or non-transport for a dinosaur tooth on the basis of its fresh and unabraded appearance" (Argast et al., 1987, p. 930). Thus, some reworked vertebrate fossils have "transport induced abrasion" (e.g., Burris, 2001, p. 37), whereas others do not (Argast et al., 1987; Eaton et al., 1989).

Trueman & Benton (1997) advocated using REE (Rare Earth Element) compositions as an aid to identifying reworking. Thus, a reworked fossil may have a different REE composition than the enclosing sediment and may have identical REE to the underlying stratum from which it originated. This method, however, does not work if the REE composition of the sediment in which the fossil originated is the same as the REE composition of the sediment into which it was reworked. The only use of REE composition in claims of Paleocene dinosaur fossils was by Fassett et al. (2002) and Fassett (2009). It did not demonstrate a difference in REE values between the supposed Paleocene dinosaur fossil and dinosaur fossils from underlying, unquestionably Upper Cretaceous strata (Lucas et al., 2009).

Therefore, there remains no hard and fast criterion to decide whether a vertebrate fossil has been reworked. This makes it impossible to exclude definitely some of the reports of Paleocene dinosaur fossils, though, as discussed later, I argue that the onus is on those who claim to have found Paleocene dinosaur fossils should demonstrate that such fossils are not reworked.

REPORTS OF PALEOCENE DINOSAURS

Although reports of Paleocene dinosaur fossils are few, they are geographically widespread, having been made in Europe, Africa, North America, South America, the South Pacific, and Asia (Fig. 1).

Europe

Only one claim of Paleocene dinosaurs has come from Europe, particularly from Spain. Thus, Royo Gómez (1928) reported two teeth he identified as theropod dinosaurs from Eocene strata (these strata are Eocene, not Paleocene) at Llamquique in the Oveido basin of Asturias. These teeth apparently have disappeared, but based on archival photographs and the discovery of another similar tooth at Llamaquique, Pered Superbiola et al. (2012) concluded that they are ziphodont crocodilian teeth, not dinosaur. This claim of an Eocene dinosaur was thus based on a misidentification.

Africa

As with Europe, there appears to have been only one claim of a Paleocene dinosaur from Africa, from Nigeria. Nopcsa (1925) described reptilian fossils, including some vertebrae he identified as those of a hadrosaurian dinosaur, from Sokoto Province. These are from the Ameki Formation, strata of Eocene age (Arua & Rao, 1987). However, Swinton (1930) later demonstrated that the supposed hadrosaur vertebrae are actually crocodilian (also see Lamanna et al., 2004). So, this is also a Paleocene dinosaur claim based on a misidentification.

North America

Most of the claims of Paleocene dinosaurs come from the western United States and include the earliest such claims.

The Laramie problem

The "Laramie problem" was a debate, primarily between palaeobotanists and other palaeontologists and geologists, over the age of coal-bearing strata in the American West, which are called Laramie Formation in part of Wyoming-Colorado. This name was also used as "Laramie Series" to refer to all of the strata between marine Cretaceous rocks of the Montana Group (a term long abandoned) and unquestionably Paleocene strata of the Fort Union Formation (Veatch, 1907). This debate lasted about 50 years, from the 1870s to the 1920s. The core of the Laramie problem was the assignment by some 19th-century palaeobotanists of a Cenozoic age (Eocene to Miocene) to fossil plants found in strata that also contained dinosaur fossils (Fig. 2).

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Fig. 2 - Fossil plants such as these, from the Laramie Formation of Colorado, co-occurred with dinosaur fossils and were regarded by 19th Century palaeobotanists as of Cenozoic age (from Knowlton, 1922, plate 3).

Waage (1975) provided a brief summary of the Laramie problem (see Knowlton, 1922 and Merrill, 1924 for much longer reviews). It began with the idea of Hayden (1867) that in the western USA, the K/Pg boundary was marked by the transition from marine strata (with ammonoids) to lacustrine strata (many coal-bearing) with dinosaur fossils and a palaeoflora deemed Eocene (or even Miocene) by palaeobotanists, particularly Lesquereux (1873). This was a miscorrelation of the palaeoflora based on the fact that the angiosperm-rich American floras differed from European Cretaceous floras and more resembled European Eocene floras (Knowlton, 1922) (Fig. 2). Arguments, such as those of Stevenson (1875), that this likely reflected climatic similarities between the European Eocene and the American Late Cretaceous were generally ignored.

Nevertheless, Nineteenth Century vertebrate palaeontologists rejected the conclusion that dinosaurs lived during the Cenozoic. Thus, the two leading American vertebrate palaeontologists of the late 1800s, O. C. Marsh and E. D. Cope, saw dinosaurs as restricted to the Mesozoic. Indeed, Cope (1898, p. 60) posthumously published a chart that depicted the dinosaurs having an existence

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that spanned the entire Mesozoic. One of the foremost American experts on fossil mammals, W.D. Matthew (1914) also rejected the notion of Cenozoic dinosaurs.

After decades of disagreement, the Laramie problem was fully resolved when Knowlton (1922), a premier palaeobotanist of the U. S. Geological Survey, rejected the correlations of Lesquereux and others. No megafossil plants of Cenozoic age are associated with or stratigraphically below dinosaur fossils in the American West.

New Mexico

The San Juan Basin of northwestern New Mexico-southwestern Colorado (Figs. 1, 3) has a long and complicated history of claims of Paleocene dinosaurs that extends back for more than a century. The main events of that history are as follows:

1) Brown (1910) provided the original stratigraphic context for the stratigraphically highest dinosaur fossils in the San Juan Basin, naming the strata that contain these fossils the "Ojo Alamo Beds". Although Brown did not properly define the Ojo Alamo Beds, Bauer (1916) did. In the west-central San Juan Basin, where it yields most of its dinosaur fossils, the Ojo Alamo is a tripartite unit: lower conglomerate, middle "shale" (mostly siltstone and fine sandstone) and an upper conglomerate. Baltz et al. (1966) restricted the name Ojo Alamo to the upper conglomerate, reassigning the underlying Ojo Alamo formation strata to the Kirland Formation as the newly named Naashoibito Member. However, current palaeontological practice (e.g., Lucas & Sullivan, 2000; Sullivan et al., 2005) recognises the tripartite Ojo Alamo of Bauer (1916) and terms the lower conglomerate and middle "shale" the Naashoibito Member and the upper conglomerate the Kimbeto Member of Powell (1973) (Figs. 3-4). The stratigraphically highest in situ dinosaur fossil are from the Naashoibito Member (e.g., Jasinski et al., 2011).
2) Following up on Brown's work, in 1913 Princeton University stratigrapher and palaeontologist William J. Sinclair worked with Walter Granger of the American Museum of Natural History to locate precisely the K/Pg boundary in the San Juan Basin (Sinclair & Granger, 1914; Lucas, 2023). Sinclair's work embodied what would later be recognised as a mistake—it placed the Cretaceous-Paleogene boundary at the top of the "Ojo Alamo beds" of Brown (1910). This was based on a dinosaur (hadrosaur) caudal vertebra found loose on the top of the Ojo Alamo Sandstone. As Sinclair & Granger (1914, p. 301) stated, "the centrum of a dinosaur caudal vertebra was found, loose on the surface, by Mr. Jack Martin of the expedition, resting on this sandstone [upper conglomerate of the Ojo Alamo Sandstone of later usage] in the immediate vicinity of Barrel Spring". They went on to conclude (p. 301) that "it was not in place, but it seems hardly probable that it had been carried to the spot where it was found by the Indians, who are afraid of fossil bones". However, later studies would demonstrate that the highest *in situ* dinosaur fossils are stratigraphically lower, in the beds now called the Naashoibito Member of the Ojo Alamo Formation (e.g., Fassett et al., 1987; Lucas et al., 1987; Sullivan et al., 2005; Flynn et al., 2020). So, the loose caudal vertebra at Barrel Spring was reworked, either by human agency or by sedimentary processes.
3) The conglomeratic sandstone that dinosaur vertebra lay on has long been regarded as Paleocene in age based on palynology (Anderson, 1960; Baltz et al., 1966; Tschudy, 1973; Fassett, 1973, 2009; Newman, 1987; Lucas et al., 1987; Sullivan et al., 2005).
4) Powell (1973, p. 188-119) reported dinosaur bone fragments as much as nine m above the base of the Kimbeto Member of the Ojo Alamo Formation at a locality along a tributary of Hunter Wash. He noted that these fossils were "waterworn and undiagnostic", and assigned them to dinosaurs simply based on their relatively large size. He considered these dinosaur fossils to not be reworked but instead to indicate that the lower part of the Kimbeto Member is Cretaceous. However, Lucas (1981, p. 346, text-fig. 15.8f) relocated Powell's bone site and noted the waterworn nature of the bones and their direct association with conglomerate and fossil logs. He argued that the bones were reworked in this high-energy deposit.

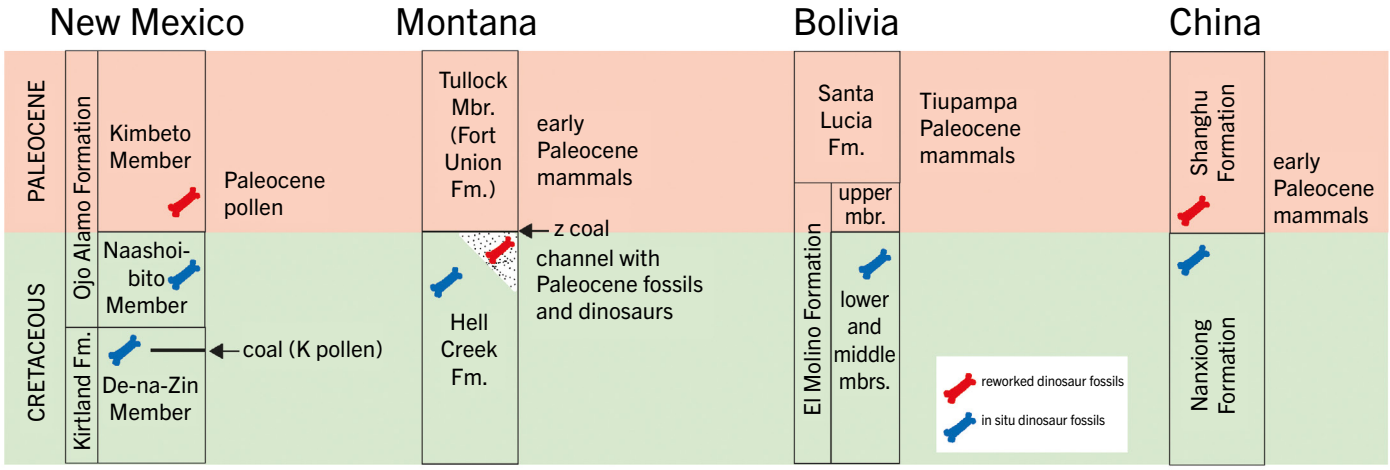

Fig. 3 - Simplified stratigraphy of the main claims of Paleocene dinosaur fossils from New Mexico, Montana, Bolivia and China. Only in situ and reworked dinosaur records and a few other key age indictors are indicated. Note that vertical scale is not thickness. See text for discussion.

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5) Fassett et al. (1987) reviewed records of dinosaur bones from the Kimbeto Member to conclude that all are obviously reworked except perhaps a hadrosaur femur found along the San Juan River (Fig. 5), which is stratigraphically above a palynomorph assemblage deemed to be Paleocene (Fassett & Lucas, 2000; Fassett, 2009). Other than this bone, the other dinosaur specimens in the Kimbeto Member are isolated, incomplete and/or abraded in a high-energy fluvial unit of crossbedded sandstone and conglomerate. The obvious conclusion is that these bones are reworked from underlying Upper Cretaceous strata. The isolated hadrosaur femur is isolated in a high-energy fluvial deposit, aligned with current indicators. It was obviously transported, and, despite its relatively good state of preservation, later workers concluded it is reworked (Sullivan et al., 2005; Lucas et al., 2009).
6) Fassett et al. (2002) claimed to have recovered Paleocene palynomorphs from a coal bed high in the Kirtland Formation, just below the Naashoibito Member dinosaur assemblage (Fig. 4). However, repeated sampling of that coal bed by Sullivan et al. (2005) only yielded Late Cretaceous palynomorphs.
7) Earlier work by Fassett found amplification in a very long article published by Fassett (2009), which met with a rebuttal by Lucas et al. (2009), who stated:

a) We conclude that Fassett (2009) has failed to produce the compelling evidence needed to support his extraordinary claim that Paleocene dinosaur fossils are present in the San Juan Basin. Existing data do not uniquely support his claim. Thus, only one arguably reworked hadrosaur femur is stratigraphically above undisputed Paleocene pollen. So, palynology does not demonstrate Paleocene dinosaurs in the San Juan Basin. Nor does magnetostratigraphy, because (among other things) Fassett's disregard of a major unconformity above the dinosaur-bearing Naashoibito Member renders questionable his use of magnetostratigraphic correlation to assign a Paleocene age to dinosaur fossils in that unit. Moreover, Fassett's (2009) article failed to adequately dismiss the broadly held conclusions that: (1) the K/T boundary is within the Ojo Alamo Sandstone; (2) the dinosaur-dominated assemblage of the lower Ojo Alamo Sandstone (Alamo Wash local fauna of the Naashoibito Member) is of Maastrichtian age; and (3) the isolated, water-worn and/or fragmentary dinosaur bones from the overlying Kimbeto Member are reworked from underlying Cretaceous strata.

8) Fassett et al. (2011) published U-Pb ages done directly on dinosaur bones that they believed are Paleocene, and obtained some Paleocene ages (and even some ages as young as

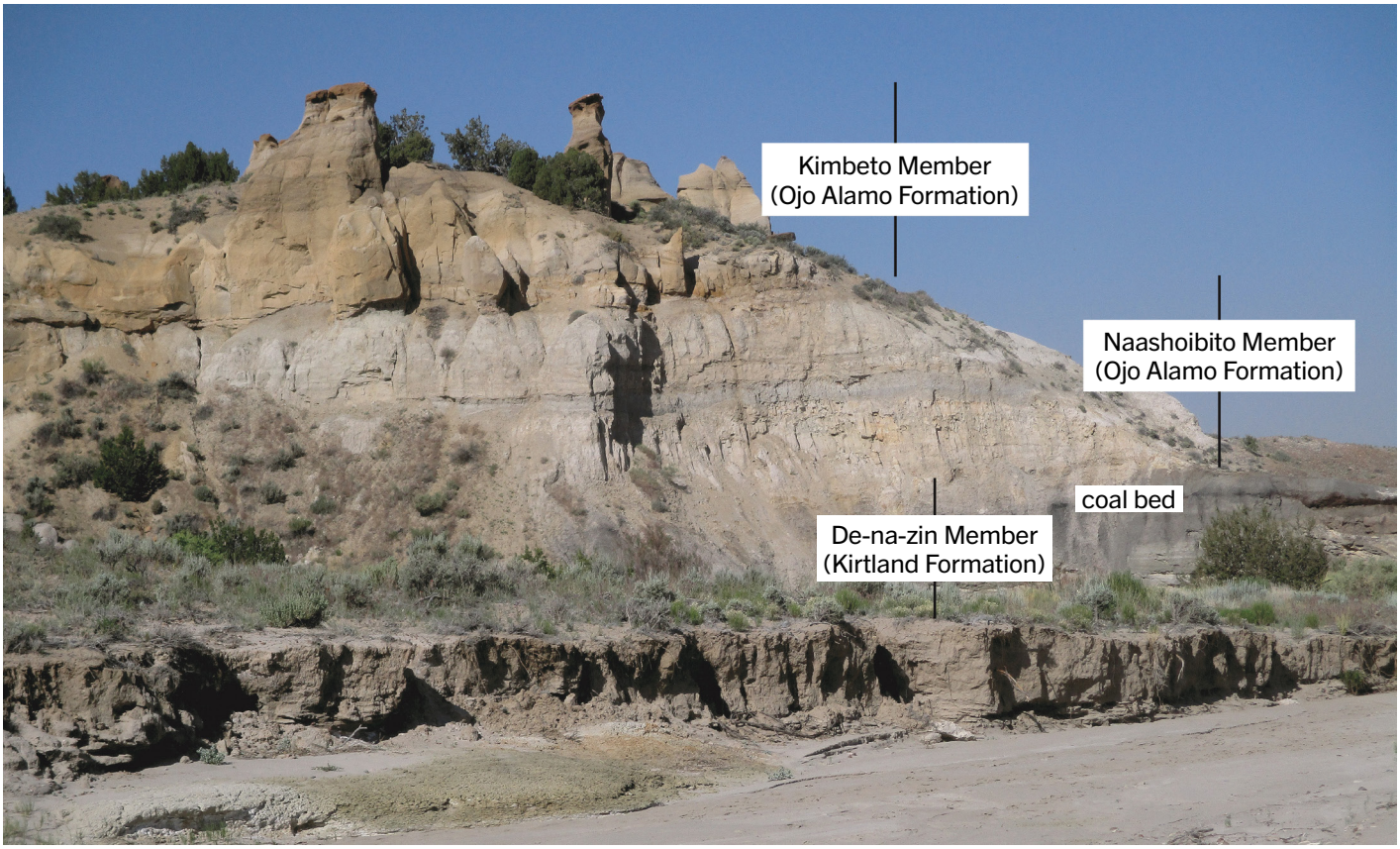

Fig. 4 - Photograph of strata across the K/Pg boundary near Barrel Springs in the San Juan Basin, New Mexico, USA. The Naashoibito Member of the Ojo Alamo Formation contains the stratigraphically highest *in situ* dinosaur fossils in this section, whereas dinosaur bones in the overlying Kimbeto Member (which also contains Paleocene palynomorphs) have been judged to be reworked. The coal bed high in the De-na-Zin Member of the Kirtland Formation was claimed to contain Paleocene palynomorphs, but repeated sampling only recovered Late Cretaceous palynomorphs (Sullivan et al., 2005). See text for further discussion.

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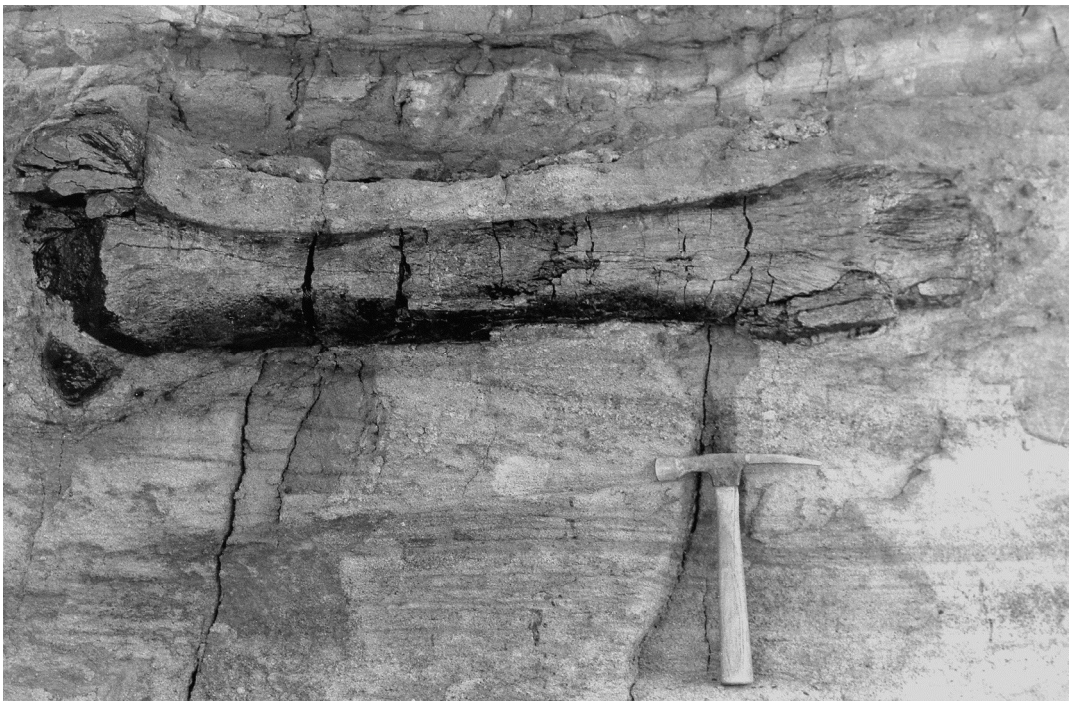

Fig. 5 - Isolated hadrosaur femur in the Kimbeto Member of the Ojo Alamo Formation along the San Juan River in the San Juan Basin. New Mexico, USA. This bone is stratigraphically above Paleocene palynomorphs (from a mudrock stratum below the sandstone in the photograph). This isolated bone in a high-energy fluvial deposit has obviously been transported and is very likely reworked (see text for discussion).

Miocene). This work met with immediate criticism (e.g., Koenig et al., 2012) that noted the extensive research attempting to date bones that revealed that what is actually being dated are recrystallisation ages, not the original age of the fossil bone (cf. Chew et al., 2011). The radioisotopic ages of the dinosaur bones published by Fassett et al. (2011) have thus been rejected.

So, the various claims of Paleocene dinosaur fossils in the San Juan Basin have been based on reworked fossils or on incorrect age assignments (Lucas et al., 2009; also see Flynn et al., 2020). No Paleocene dinosaur fossils have been demonstrated from the San Juan Basin.

Colorado

The Cretaceous-Palaeogene succession of strata and fossils in the Raton Basin of northeastern New Mexico-southeastern Colorado and the Denver Basin immediately to the north is now understood in some detail. Indeed, the first evidence in nonmarine strata of the iridium anomaly that marks the K/Pg boundary was discovered in the Raton Basin (Fig. 6). However, there are no dinosaur bones known from the Raton Basin, but there is an extensive record of palynomorphs and megafossil plants important to palaeobotanical placement and correlation of the K/Pg boundary (e.g., Tschudy et al., 1984; Wolfe & Upchurch, 1987).

In the Denver Basin of Colorado, Lee (1913) reported Paleocene ("Eocene") dinosaurs (identified by C. W. Gilmore as ceratopsian) from the Dawson Arkose at a locality that overlooks the valley of Jimmy Camp Creek, which is near Colorado Springs. The Paleocene age was based primarily on the conclusion that these fossils were stratigraphically associated with a "creodont" tibia and Paleocene plant fossils.

Brown (1943, p. 75) reviewed this claim, noting that the dinosaur bones reported by Lee (1913), which were never described or illustrated, "seem to be lost", so their identity could not be verified. In checking the stratigraphy of the site of Lee's supposed Paleocene dinosaurs, Brown (1943) identified a 183 m thick stratigraphic section with Cretaceous fossil plants and dinosaur bones in the lower 152 m of that section. At a separate, nearby locality a Paleocene mammal (a "creodont") tibia was found stratigraphically above Cenozoic plant fossils. Brown (1943, p. 75) concluded that Lee's "dinosaur" bones came from a nearby locality stratigraphically below the mammal tibia, noting that Lee's locality was in or very near strata that yielded Cretaceous plant fossils. Brown concluded that "the Cretaceous-Tertiary boundary here, as at Golden, separates Cretaceous dinosaurs from diagnostic Tertiary mammals and plants". Indeed, later studies of the Late Cretaceous dinosaurs in the Denver Basin (e.g., Carpenter & Young, 2002) make no mention of Lee's Paleocene dinosaurs. Lee's (1913) report of Paleocene dinosaurs from the Denver Basin was thus based on mistaken stratigraphy.

Montana

In eastern Montana (and in the nearby states of North and South Dakota) the Upper Cretaceous Hell Creek Formation contains the most extensive and most studied record of dinosaur extinction (see, for example, volumes edited by Hartman et al., 2002 and Wilson et al., 2014, and more recent articles such as Sprain et al., 2015). The Hell Creek Formation is fluvial strata overlain by fluvial Paleocene strata of the Tullock Member of the Fort Union Formation. A coal bed (the "Z coal") marks the formation boundary, which is very close to though diachronous across the K/Pg boundary (Fig. 3). Both the Hell Creek Formation and Tullock Member have been the subject of diverse studies of their fossil record as well as of the iridium-rich clay layer, magnetostratigraphy, radioisotopic dating and isotope stratigraphy. Claims of Paleocene dinosaur fossils in the Hell Creek Formation are from outcrops in eastern Montana, in McCone and Garfield counties.

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In an abstract, Rigby (1985) first posited the presence of Paleocene dinosaurs in this outcrop area. Sloan et al. (1986) provided more detailed documentation of the claim. They reported a river-channel deposit high in the Hell Creek Formation that contains teeth of early Paleocene mammals, seven dinosaur species and Paleocene pollen that they judged to postdate the iridium anomaly that marks the K/Pg boundary (Fig. 3). They regarded the dinosaur fossils as "unreworked teeth of seven genera of dinosaurs" (Sloan et al., 1986, p. 630). These were identified as theropod (*Albertosaurus*, *Dromaeosaurus*, new genus, *Paronychodon*), ornithopod (*Thescelosaurus*, *Edmontosaurus*) and ceratopsian (*Triceratops*). These claims of Paleocene dinosaur fossils met with immediate criticism (e.g., Retallack & Leahy, 1986; Fastovsky, 1987; Argast et al., 1987).

Rigby et al. (1987) elaborated on these supposed Paleocene dinosaur fossils, arguing that they are not reworked and are of Paleocene age, illustrating some of the dinosaur teeth (their fig. 6). They stated that "dinosaur teeth from each reported Paleocene locality retain minute serrations and a sharp basal edge such delicate edges would have been worn by even limited abrasion" (Rigby et al., 1987, p. 300) (Fig. 7). They went on to emphasise that "there is no reasonable process known to us to cause these dinosaur remains to be exhumed from Cretaceous deposits, carried into the channels intact, exposed to the rigors of traction transport, and yet retain their pristine nature" (p. 300). Rigby et al. (1987, p. 302) concluded that the following factors argued against reworking of the dinosaur fossils in the channels: "(1) unabraded state of dinosaur fossils, (2) common and almost exclusive association with fossil forms that 'cannot' have been reworked, (3) absence of Cretaceous mammal forms that would likely be present if reworking had occurred, and (4) rare elements in the collective fauna appear as major constituents in some collections; reworking would certainly serve to reduce this abundance". Rigby (1987), among other publications, repeated and amplified these arguments.

However, several workers noted that the channels that bear the supposed Paleocene dinosaur fossils are incised into Upper Cretaceous strata, so they advocated reworking of the teeth (Smit & Van der Kaars, 1984; Bryant et al., 1986; Fastovsky & Dott, 1986; Retallack et al., 1987; Fastovsky, 1987; Lofgren et al., 1990). Lofgren et al. (1990, p. 876) presented an analysis of one of the channels and its fossils to conclude that "the close association of bones [including dinosaurs] and large angular mudstone clasts, their basal position in the channel, and absence of abrasion to the bones indicate that the dinosaur elements were introduced into the channel as a result of erosion of pre-exiting strata". This seems to have been the last word on the supposed Paleocene dinosaur fossils from Montana and was readily accepted by most palaeontologists as the final evidence of these fossils being reworked. Indeed, the idea of Paleocene dinosaurs in the Montana section has disappeared from recent discussions of dinosaur extinction in the Hell Creek Formation (e.g., Pearson et al., 2002; Sprain et al., 2015).

South America

A claim of Paleocene dinosaurs in Bolivia dates to the 1980s, whereas claims in Argentina date to the early 1900s (Fig. 1).

Bolivia

The discovery in 1980s of the Tiupampa vertebrate fossil (mostly mammal) assemblage in central Bolivia added the oldest Paleocene vertebrate fossils to the South American record.

Fig. 6 - The iridium-rich (impact) clay layer in nonmarine strata that marks the K/Pg boundary in the Raton Basin, New Mexico, USA.

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Fig. 7 - Small theropod dinosaur tooth from channel deposit in upper Hell Creek Formation of Montana found associated with Paleocene palynomorphs and mammal fossils. The high quality of preservation of this tooth (note, for example, the serrations on its posterior edge) was invoked to argue that the tooth is not reworked. Tooth crown is about 11 mm tall. Photograph courtesy of the late J. Keith Rigby, Jr.

However, the original reports of the stratigraphic context of these fossils stated that the Tiupampa mammal fauna comes from the El Molino Formation (e.g., Muzion et al., 1983, 1984), a stratigraphic unit that contains Cretaceous fossils in its lower and middle members (Gayet et al., 1991; Marshall et al., 1997) (Fig. 3). Thus, the lower and middle members of the El Molino Formation yield diverse vertebrate fossil assemblages (especially of marine fishes) considered to be of late Campanian-Maastrichtian age (see review by Gayet et al., 1991). The dinosaur fossils of the El Molino Formation are dinosaur footprints (e.g., Leonardi, 1994) and a single theropod tooth (Marshall, 1989).

The upper member of the El Molino Formation is regarded as a stratigraphic equivalent of the Tunsal Formation of northwestern Argentina, which has produced Paleocene palynomorphs (Quattrochio et al., 1986). So, the K/Pg boundary is placed between the middle and upper members of the El Molino Formation (Fig. 3).

Based on the early mistaken assignment of the Tiupampa fossil mammals to the El Molino Formation, Van Valen (1988) suggested that these Paleocene mammals co-occur with the dinosaur footprints in that unit. However, the Tiupampa Paleocene mammal fossils actually are from the Santa Lucía Formation, which overlies the El Molino Formation (Fig. 3). Magnetostratigraphy, sequence-stratigraphic correlations and the Tiupampa mammals establish a Paleocene age for the Santa Lucia Formation, mostly in Selandian magnetochron 26R, which is ~59-62.5 Ma (Marshall et al., 1997; Speijer et al., 2020). Thus, there is no direct association of dinosaur fossils with Paleocene mammal fossils in central Bolivia; the Paleocene mammal fossils are stratigraphically well above the dinosaur fossils. Van Valen's (1988) claim of Paleocene dinosaurs in Bolivia was based on a stratigraphic error.

Argentina

The famous Argentinian vertebrate palaeontologist Florentino Ameghino thought that many groups of placental mammals originated in Argentina. To support that conclusion, Ameghino (1900, 1902, 1906) assigned the oldest mammal fauna from Patagonia known to him, that of the "*Notostylops* beds", a Cretaceous age. He supported that conclusion by claiming that dinosaur fossils had been found associated with mammal fossils from the *Notostylops* and the overlying *Astraponotus* beds. Some, however, saw this instead as evidence of Cenozoic dinosaurs, using the mammals as the age indicators. Roth (1898, 1899, 1900, 1908) claimed to have found dinosaur fossils stratigraphically above the *Notostylops* fauna, but Simpson (1932a, 1932b) demonstrated those claims were unverifiable or based on erroneous stratigraphy. The *Notostylops* fauna is now regarded as representative of the early Eocene Casamayoran LMA (Flynn & Swisher, 1995).

Simpson (1932a, 1932b) critically evaluated the claimed association of dinosaur fossils with Cenozoic fossil mammals in Argentina to conclude that no such association had been demonstrated. At least some of the so-called dinosaur teeth identified by Ameghino (1906) are actually those of crocodilians, namely sebecosuchians, which have teeth that much resemble those of some theropod dinosaurs (Langston, 1956; Molnar & Vasconcellos, 2016). Thus, no data from Argentina demonstrate *bona fide* dinosaur fossils associated with or stratigraphically above mammals of the *Notostylops* beds. Claims of Paleocene dinosaur fossils from Argentina were based on misidentifications, erroneous stratigraphy and/or incorrect geologic age assignments.

South Pacific—Chatham Islands

The Chatham Islands east of New Zealand (~ 865 km east of Christchurch) are eroded remnants of isolated oceanic islands that are at the eastern end of the Chatham Rise, a submarine extension of the New Zealand microcontinent. On the islands, a thick succession of Cretaceous-Palaeogene strata includes the Takatika Grit, a relatively thin (~10 m thick), shallow marine deposit of glauconitic, volcaniclastic sandstone and siltstone (Stillwell et al., 2006). Microfossils (primarily dinoflagellates) indicate an age range of mid-Campanian through Paleocene for the Takatika Grit (Stilwell et al., 2006). Clearly, this is a condensed deposit, and reworking and leakage of fossils are common in such deposits (Baraboshkin, 2009). Vertebrate fossils in the Takatika Grit include theropod dinosaur bones (Fig. 8), shark teeth and marine reptile bones (Stilwell et al., 2006; Consoli & Stilwell, 2009; Stilwell & Håkansson, 2012). The bones are associated with phosphatic nodules, some of which contain bone. All of these bones are incomplete and abraded (Fig. 8).

Stilwell et al. (2006, p. 245) stated that "the mixed latest Cretaceous-earliest Tertiary age of associated microfossils indicate that the K-T boundary may be present below the exposed bone-rich sediments", and noted that the stratigraphically highest dinosaur bones were "in greensands together with rich dinoflagellate assemblages clearly of early- to mid-Teurian (Danian) age" and added that "these bones exhibit no signs of reworking". Stilwell & Håkansson (2012, p. 803) reiterated that "these bones exhibit no evidence at all of reworking and are very well preserved" and went on to state that "the possibility remains that small non-avian theropods survived the K-T extinction event for a short time slice on a remote strip of land in the SW Pacific".

Nevertheless, I question the claims that the bones are "well preserved" and "show no signs of reworking". The Chatham Islands

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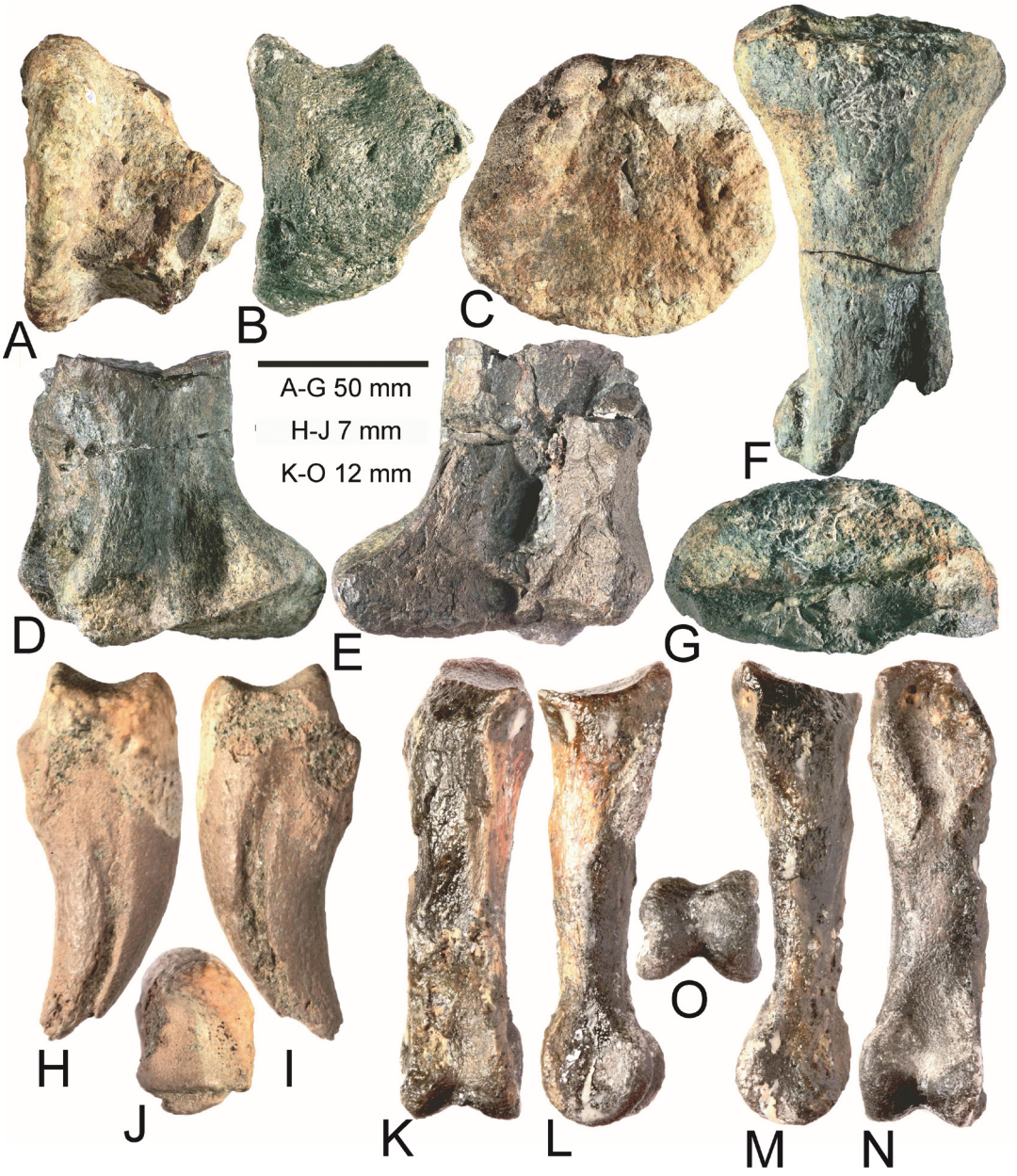

Fig. 8. - Supposed Paleocene dinosaur bones from the Takatika Grit on the Chatham Islands in the South Pacific. (A-C) Partial theropod vertebral centrum. (D-E) Probable theropod proximal head of tibia. (F-G) Probable theropod proximal pedal phalanx II-1 or III-1. (H-J) Theropod manual ungual. (K-O) Manual phalanx of a theropod. Modified from Stilwell et al. (2006, fig 3), with photographs courtesy of Jeffrey Stilwell.

dinosaur bones are isolated and broken, and the broken edges have clearly been smoothed by abrasion (Fig. 8). Characteristically Cretaceous marine reptile (plesiosaur and mosasaur) bones from the Takatika Grit are mostly abraded vertebral centra (Consoli & Stilwell, 2009). The strata that contain them are shallow marine, condensed and contain phosphate nodules and marine microfossils; the latter suggest an age range of Campanian-Paleocene for a unit only 10 m thick, clear evidence the Takatika Grit is a condensed deposit likely characterised by mixing and reworking. Thus, I conclude that the supposed Paleocene dinosaur fossils from the Chatham Islands are reworked.

China

The Nanxiong basin in Guangzhou Province, southern China, is a fault-bounded graben that is ~ 80 km long NE-SW and less than 20 km wide. It preserves an important record of fossil vertebrates across the K/Pg boundary (Fig. 3). The basin fill across the K-Pg boundary is fluvial siliciclastic red beds that are mostly purplish red mudstones with some interbedded sandstones and conglomerates. Late Cretaceous dinosaur fossils from the Nanxiong Formation are bones, eggs and nests of eggs, whereas the overlying Shanghu Formation contains Paleocene mammals (Fig. 3).

A diverse literature exists about the K/Pg boundary in the Nanxiong basin (e.g., Sloan, 1987; Russell & Zhai, 1987; Zhao et al., 1991, 2002; Mateer & Chen, 1992; Rigby et al., 1993; Russell et al., 1993; Hansen et al., 1994; Buck et al., 2004; Erben et al., 1995; Stets et al., 1996; Taylor et al., 2006; Clyde et al., 2010; Ma et al., 2018). Taylor et al (2006) provided a comprehensive and critical review of previous work on the K/Pg boundary in the Nanxiong basin, noting that since the 1960s there have been four different placements of that boundary in the basin.

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These different placements are based on magnetostratigraphy, radioisotopic ages, geochemistry, micropalaeontology (pollen, charophytes, ostracods) and vertebrate biostratigraphy, particularly of dinosaur eggs and eggshell fragments. There is no definitive iridium anomaly that marks the K/Pg boundary in the Nanxiong basin, though small iridium anomalies are present in dinosaur eggshells at four stratigraphic levels (Zhao et al., 2002).

Taylor et al. (2006) concluded that the best evidence places the K/Pg at the contact of the Nanxiong and Shanghu formations (Fig. 3). This fits the conclusions of most workers, well expressed by Russell & Zhai (1987), who concluded there is about a 1 m thick stratigraphic interval between the highest *in situ* Late Cretaceous dinosaur fossils and the lowest in situ Paleocene mammal fossils. Magnetostratigraphy places the Shanghu Formation base in chron 29R (e.g., Clyde et al., 2010; Ma et al., 2018) and stratigraphically above the highest dinosaur eggs and nests (which are difficult to impossible to rework) and below fossils of Paleocene mammals. Buck et al. (2004) noted that there are debris flow and mudflow deposits in both the Nanxiong and Shanghu formations, arguing that dinosaur eggshell fragments in such deposits are reworked.

Part of the discussion of the K/Pg boundary in the Nanxiong basin centred on the age of the oldest fossil mammals of the Shanghu Formation, the *Bemalambada* fauna characteristic of the Shanghuan LMA (Russell & Zhai, 1987). These are endemic mammals more primitive than North American Torrejonian relatives, so, as reviewed by Lucas & Williamson (1995), this suggests a Puercan (earliest Paleocene) age of the Shanghu mammals (also see Russell & Zhai, 1987; Lucas, 1993). However, Sloan (1987) considered (without justification, in my view) the Shanguan LMA a correlative of the Torrejonian LMA, which is after the Puercan (about 61-64 Ma: Lofgren et al., 1990, 2004). This correlation would generate a biochronologic gap equivalent to the Puercan LMA (about 1-1.5 million years: Lofgren et al., 1990) in the Nanxiong section that could be filled with the stratigraphically highest dinosaur fossils. However, a much more strongly supported correlation to the Puercan LMA indicates that the stratigraphically lowest Shanghu Formation fossil mammals are about 65-66 Ma, very close in age to the K/Pg boundary, and stratigraphically overlie *in situ* Upper Cretaceous dinosaur fossils.

Thus, there is no basis for identifying Paleocene dinosaur fossils in the Nanxiong basin. Such claims were based on incorrect placement of the K/Pg boundary and on reworked dinosaur eggshell fragments.

PALEOCENE DINOSAURS: CRITERIA

Claims of Paleocene dinosaurs have been based on misidentifications of fossils from Paleocene strata as dinosaurs, assignment of incorrect stratigraphic positions or geologic ages to the supposed Paleocene dinosaur fossils and/or reworking of Cretaceous dinosaur fossils into Paleocene rocks. From these errors, we can identify the criteria by which any claim of a Paleocene dinosaur fossil must be evaluated.

Misidentifications

Most misidentified fossils claimed to be Paleocene dinosaurs are those of crocodilians, and particularly the theropod-dinosaur-like (ziphodont) teeth of sebecosuchian crocodilians. At present, given the extensive knowledge of dinosaur morphology and that of other vertebrate fossils (especially that of crocodilians), the likelihood of a supposed Paleocene dinosaur fossil belonging to another group of reptiles seems unlikely. Still, supposed Paleocene dinosaur fossils must be correctly identified as dinosaurian.

Incorrect stratigraphic position and/or geologic age

The presence of a dinosaur fossil is usually taken to indicate an age no younger than Late Cretaceous, so there must be strong evidence that a dinosaur fossil is Paleocene that overrides the evidence of geologic age that the dinosaur fossil, itself, provides. Biostratigraphically, such evidence has mostly come from palynology and mammals, which do allow Cretaceous and Paleocene ages to be distinguished. However, palynomorphs can be reworked or suffer leakage (younger grains introduced into older strata), and such reworking/leakage may not be easily detected by the preservation of the palynomorphs. The association (contemporaneity) of dinosaur fossil(s) with *bona fide* fossils (or other Paleocene age indicators) is essential to claiming a dinosaur fossil is Paleocene.

Reworking

As discussed above, identifying reworked fossils is not always straightforward, especially in the case of small fossils. Thus, the dinosaur teeth from Montana found in channel lags with Paleocene mammal teeth are often little abraded, preserving fine details of crown morphology (Fig. 7). Other than their occurrence as isolated teeth, their condition does not provide compelling evidence that they have been reworked. The presence of the fossils in fluvial channel deposits, which are high-energy deposits that often scour into and recycle material from underlying strata, may be the best evidence of reworking in such a situation.

As was made clear earlier, there is no agreed-upon method that always distinguishes reworked teeth/bones from those that are not reworked. Thus, Rigby, Sloan and their collaborators considered the dinosaur teeth in upper Hell Creek Formation channel deposits that are associated with Paleocene mammal fossils and palynomorphs to not be reworked, but other palaeontologists concluded they were reworked. Stillwell and co-authors considered the dinosaur bones associated with Paleocene dinoflagellates in the Chatham Islands to not be reworked, but I think they are reworked. Disagreements about reworking will continue to be part of the quest for Paleocene dinosaur fossils.

I recommend that the default position (null hypothesis to be tested) should be considered as reworked any dinosaur fossils found in strata associated with or stratigraphically above *bona fide* Paleocene fossils. The burden of proof should be on demonstrating that the dinosaur fossils are not reworked, though that may not always be possible.

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CONCLUSIONS

Based on the above, I conclude that nobody has published convincing evidence to support assigning a Paleocene (or younger) age to a dinosaur fossil. Claims of Paleocene dinosaurs have been based on misidentifications (Spain, Nigeria, Argentina), incorrect stratigraphy/age assignments (Colorado, New Mexico, Bolivia, China) or of dinosaur fossils apparently reworked from Upper Cretaceous strata (New Mexico, Montana, Chatham Islands). The reworked records are most important because they hold the best possibility of being *bona fide* Paleocene dinosaur fossils. This is because identifying or discounting reworking remains a somewhat uncertain, subjective process. Nevertheless, the case for the reworking of the so-called Paleocene dinosaur fossils in New Mexico, Montana and the Chatham Islands is a strong one. The burden of proof has not been met by those who claim that those dinosaur fossils are not reworked.

Planet Earth is a huge and complex place, so there is no reason to conclude a priori that dinosaurs could not have survived the end of the Cretaceous. Nonmarine plants and animals appear to have been particularly resilient to the causes of mass extinctions (Traverse, 1988; Lucas, 2021), so the possibility of dinosaur survival after the Cretaceous in a refugium(a) needs to be considered. Indeed, we have learned relatively recently that ammonoids, long thought to have suffered total extinction at the end of the Cretaceous, survived into the earliest Paleocene in refugia (e.g., Landman et al., 2015). Nevertheless, at present there is no compelling evidence of a Paleocene dinosaur fossil(s).

Although I conclude that verifiable claims of Paleocene dinosaurs have not been made, the search will go on. Indeed, I know palaeontologists who believe that some of the claims reviewed here do document Paleocene dinosaurs. Despite that, my conclusion is that of most palaeontologists—nobody has yet demonstrated a dinosaur fossil to be Paleocene.

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